Laboratory Investigations and Numerical Modeling of Loss Mechanisms in Sound Propagation in Sandy Sediments

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LONG-TERM GOALS

To develop accurate models for high frequency sound propagation in shallow water sediments.

OBJECTIVES

The scientific objectives are to: 1) quantify the relative importance of scattering and frictional losses in the attenuation of sound in sediment, 2) evaluate and improve existing models of sound propagation and, 3) develop more complete models of sound propagation which can account for the complexity of shallow water sediments.

APPROACH

The potential loss mechanisms for propagation in sandy sediments will be investigated through numerical modeling, laboratory investigations, and field data analyses. Efforts will be made to determine the relative importance of each of these mechanisms and to use these results to improve existing propagation models or to develop new theories of acoustic propagation through sand sediments.

Laboratory investigations of scatterers in glass bead sediments.

During the Sediment Acoustics Experiment 2004 (SAX04), extensive efforts were made to determine the size distribution, spatial distribution, shape, and composition of shell hash and other objects in the sediment that were larger than the average sand grain size. These data will be used in conjunction with environmental measurements to model the scattering from, and penetration into the sediment due to volume heterogeneity [1]. The data set coupled with sound speed measurements taken at the site, will also provide an opportunity to study the role of discrete scatterers in sound propagation in the sediment.

Measurements of particle size distribution made during the Sediment Acoustics Experiment 1999 (SAX99) indicated that the shell fragments had diameters as large as 10 mm. These pieces have a $ka \approx 3.5$ for a frequency of 200 kHz in the sediment. At these ka, Rayleigh scattering is not applicable and a more complicated scattering theory is necessary. In studies of the effects of atmospheric aerosols on the propagation of light, T-matrix formulations have been successful in modeling the scattering of light by distributions of non-spherical particles [2]. These methods will be utilized for the investigations of

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sediment propagation using T-matrix formulations developed by Kargl and Lim for single scatterers embedded in Biot media [3].

The models, which will be developed to capture the effects of scattering in sound propagation, will be tested in two ways. The first will be through data-model comparisons of the sound speed and attenuation measurements made during SAX99 and those made during SAX04. During SAX04, propagation measurements were made by a number of different groups to cover a broad range of frequencies at a single site.

The second test of any developed scattering theory will be performed in the laboratory using the glass bead sediments at APL [4]. Previous measurements have determined the sound speed and attenuation in these sediments in the absence of scatterers. By adding scatterers of known size and composition to a known distribution in the glass bead sediment, it will be possible to examine the extrinsic attenuation due to scattering. This is extremely difficult to do *in situ* and the laboratory setting will provide an opportunity to understand the relative importance of both scattering and other mechanisms such as grain-to-grain friction. This is extremely important for the proper determination of any intrinsic parameters which describe intergranular losses such as the models by Buckingham [5] and Chotiros [6].

Force chain and porosity variation quantification and sound propagation modeling.

To understand the importance of heterogeneity in unconsolidated media, efforts will be made to develop models that account for the presence of force chains and porosity variations. These heterogeneities will be incorporated into a Biot description of a sand sediment using perturbation theory.

Central to any attempt to incorporate heterogeneities into Biot theory is a statistical description of the variations in each media. In studies of force chains, a majority of measurements made by the granular physics community have focused on determining the probability distribution of the forces between the grains. Very little work has been done to provide statistical descriptions of the *spatial* distribution of the chains. Describing factors, such as the correlation length of these chains, is extremely important in determining the degree to which they will produce scattering in the medium.   Likewise, for porosity variations, very little work has been done to determine the spacial statistics of the porosity in either real ocean sediments or in idealized glass bead sediments.

Since the development of a proper statistical description of the medium is essential to the propagation modeling, efforts are being undertaken to statistically describe sand and glass bead sediments. During SAX04, sediment cores were collected at the experiment site and CT scans of these cores have been performed by Allan Reed at NRL-Stennis to determine the arrangement of sand particles in the core from fine-scale scans and to determine the density from courser, large-volume scans. The particle distributions from the fine-scale CT scans will be used to provide data for finite element simulations of the sediment to determine the distribution of the bulk moduli in the medium. The courser, large-volume scans will provide a direct measurement of the density and hence, the porosity variations in the medium.

A second effort is underway, in conjunction with Joseph Calantoni, also at NRL-Stennis, to perform molecular dynamics simulations of random packings of glass beads from which porosity and force chain statistics can be determined. These simulations represent an idealized medium in which we can

control the factors which affect the interactions between the grains, including normal and shear friction, the force laws governing the contact dynamics, and the size distribution of the particles. These results will provide statistical descriptions of a glass-bead medium necessary to compare theory to the results of laboratory measurements taken in glass-bead sediments[4].

WORK COMPLETED

A theory has been developed which incorporates bulk modulus heterogeneities into Biot theory using perturbation theory. This theory has been developed in collaboration with Darrell Jackson at APL-UW. In this model, the heterogeneities are assumed to be much smaller than the wavelength of the fast compressional wave and hence should not scatter energy into incoherent fast waves. However, the heterogeneities are on the scale of the slow compressional wave; this should lead to mode conversion of the fast compressional wave into the slow compressional wave. The losses due to mode conversion produce an increase in the attenuation of the fast compressional wave. This theory was presented at the 2006 meeting of the Acoustical Society of America in Providence, RI [7].

This theory has also been extended to account for porosity variations in a Biot medium where the shear modulus is negligible. By neglecting the shear modulus, this theory models the attenuation of the fast compressional wave by accounting for mode conversion from the fast into the slow compressional wave due to variations in both the bulk modulus and the porosity. Efforts are underway to introduce the shear modulus back into the theory, in which case the variations in the porosity should also lead to mode conversion of the fast compressional wave into the shear wave, potentially producing a second attenuation mechanism. This mechanism is not present when only bulk modulus variations are present.

Initially efforts to measure the heterogeneities in a granular medium using either CT scans of actual sediments or numerical simulations of spheres focused on trying to determine the variations in the bulk modulus of the medium. The theory suggests that attenuation due to these variations may be weaker than would be expected for spatial variations in the porosity. Our focus has therefore shifted to the direct measurement of the porosity variations. To determine the density and hence porosity of the sediment cores, Alan Reed has been working with experts in CT analyses of cores to determine the proper calibration needed to obtain reliable measurements.

Porosity variations have also been the focus of the particle simulations. To approximate a glass-bead pack, Joseph Calantoni has been running simulations of interacting spheres that form random packings as they are allowed to fall into a box to approximate a glass-bead pack. An example of a random packing of 13,824 spheres under the influence of gravity with periodic boundary conditions is shown in Fig. 1. The porosity of this packing, excluding the upper and lower layers, is $\beta = 0.3894$, which is similar to the porosities measured for glass spheres ($\beta = 0.384$ was measured for glass beads in water in Ref. 4). To measure the porosity in these simulations on the scale of a single sphere, Calantoni has been finalizing code that can isolate cubic sections of the simulation space and determine the portions of the spheres which lie in the boundaries of each cube.

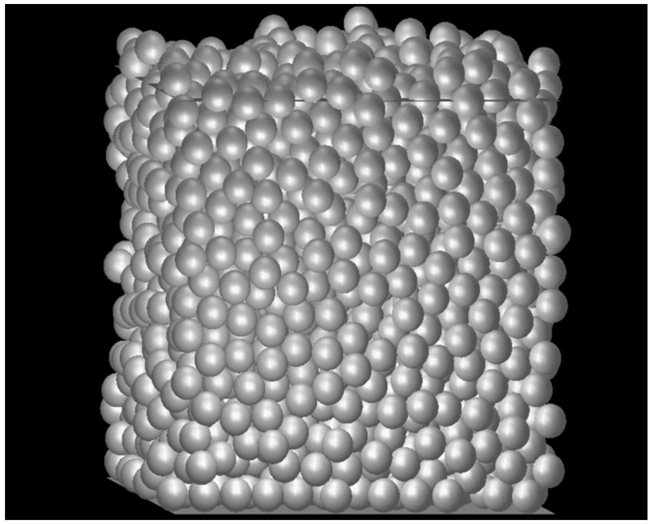

Figure 1: Random packing of 13824 spheres under the influence of gravity with periodic boundary conditions.

RESULTS

To apply the theory to sand sediments, it is necessary to know the autocorrelation function, for the spatial variations of the bulk modulus in the medium. The magnitude of the attenuation predicted by the theory is not expected to depend strongly on the form of this function therefore we have assumed an exponential autocorrelation function since it provides an analytic solution to the theory. The exponential autocorrelation function has two free parameters: the variance, σ_b^2, and the correlation length, r, of the modulus variations. Fig. 2 shows the predictions of the theory as the variance of the bulk modulus is increased from $\sigma_b^2 = 0$ to $\sigma_b^2 = (0.975\ K_b)^2$ and the correlation length is held constant at $r = 1.5d$, where d is the diameter of the grains. The remaining parameters have the same values as measured during SAX99[8].

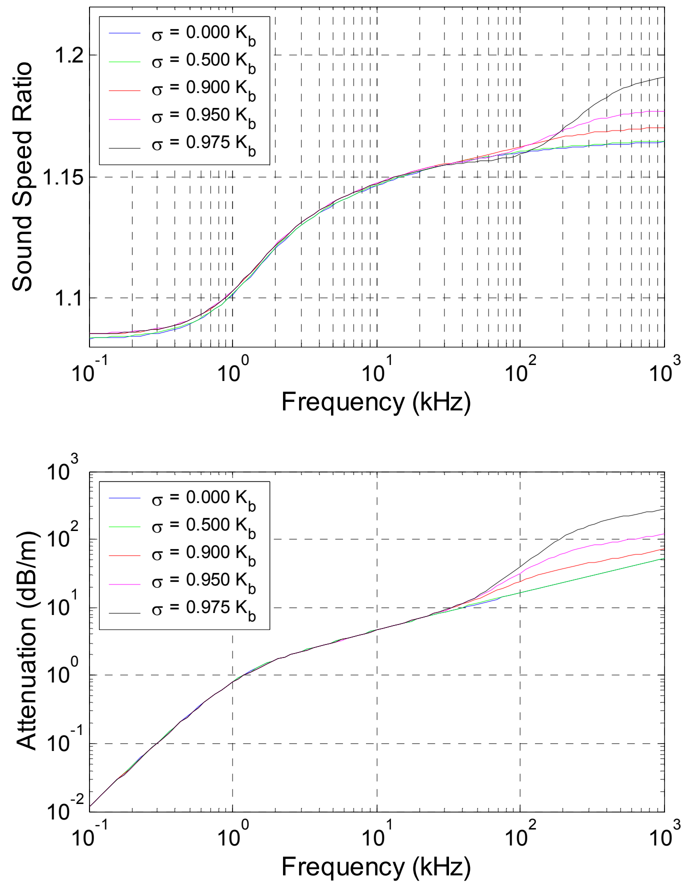

Figure 2: Theory predictions of sound speed ratio and attenuation for a Biot sediment with spatial variations in the frame bulk modulus.

These predictions indicate that at high frequencies the attenuation does not reach the levels observed during SAX99 until the square root of the variance is increased to 0.95 K_b, nearly equal to the value of the frame bulk modulus itself. It is unclear at this point whether or not these are reasonable values for the variance in a unconsolidated granular medium. Contact force measurements in dry bead packs indicate that local contact forces between the grains can be up to seven times larger than the average contact forces for the pack. Since the frame bulk modulus is a function of these contact forces, there could conceivably be large variations in the material. It remains to determine how to extract the spatial dependence of the frame bulk modulus from the local contact forces.

While the attenuation in Fig. 2 is weak for small variations in the frame bulk modulus, initial indications are that porosity heterogeneities will have a greater effect since they can produce mode conversion from the fast compressional wave into both the slow compressional wave and the shear wave. Also since both the density and Biot's coefficients (the effective moduli for the medium) are functions of porosity, the effect should be larger than that due entirely to the variations in the frame bulk modulus alone (which only influences Biot's coefficients).

IMPACT/APPLICATIONS

This work will potentially lead to the development of physically based models of sound propagation in sand sediments by examining the details of various proposed loss mechanisms such as grain-to-grain shearing and scattering.

RELATED PROJECTS

1. Title: High-Frequency Sound Interaction in ocean sediments, Grant# N00014-98-1-0040, E.I. Thorsos, PI. http://www.apl.washington.edu/projects/SAX04/summary.html The efforts of SAX04 were coordinated under this program. The determination of shell size distribution in the sediment as well as the measurement of sediment sound speed and attenuation at the SAX04 site was conducted under this program. The results of the analyses of these data will be used in the development of theories of sound propagation.

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